

# Deepwater marine protected areas of the main Hawaiian Islands: establishing baselines for commercially valuable bottomfish populations

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**ABSTRACT:** This study provides the first comprehensive fishery-independent baseline assessment of commercially important deepwater bottomfish populations across the main Hawaiian Islands. Differences in bottomfish relative abundance and size distribution were evaluated for 6 deepwater Bottomfish Restricted Fishing Areas (BRFAs). While no differences were detected in species relative abundance, evaluation of size-frequency distributions found the 2 most commercially valuable species (*Etelis coruscans* and *Pristipomoides filamentosus*) to be significantly larger inside the BRFA at Ni'ihau, located off the most remote of the main Hawaiian Islands. This BRFA is 1 of 2 ongoing BRFAs offering 10 yr of protection. This result highlighted the time it may take a long-lived and slow-growing species to show a detectable response to protection and that size distribution analyses can detect these more subtle changes. No positive effects of protection were detected for the second ongoing BRFA located off Hawai'i. Instead, 2 species (*P. filamentosus* and *P. sieboldii*) were significantly larger outside the BRFA. In contrast to Ni'ihau, the second BRFA established in 1998 originally included less preferred habitat and is next to the second largest port in Hawai'i, offering greater access, higher population pressure and more problematic enforcement. This study demonstrates that biological, sociological and environmental context must also be considered when interpreting the effectiveness of marine protected areas.

**KEY WORDS:** Hawaiian bottomfish fishery · Fishing · Fish length · Stereo video · Marine protected area

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## INTRODUCTION

Marine protected areas (MPAs) have been widely used as a tool to reduce overfishing and conserve biodiversity. Heavily exploited fish populations not only experience reduced abundance but also reduced age and size (Willis et al. 2000, Longhurst 2002, Stewart 2011). With increasing evidence that older, larger individuals produce more eggs and possibly better conditioned larvae than smaller individu-

als, removal is likely to influence population size and resilience through decreased reproductive potential (Berkeley et al. 2004, Green 2008). No-take MPAs can be used to protect targeted species by rebuilding reserves of individuals, particularly large individuals, to increase reproductive potential and resilience to fishing pressure. While there is growing evidence that MPAs can support higher abundance, biomass and size of harvested species (Russ & Alcala 1996, Halpern & Warner 2002, Willis et al. 2003), the ef-

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fectiveness of MPAs has also been found to vary considerably, both in direction and magnitude of response (Micheli et al. 2004, Russ et al. 2005). Recent reviews examining assessment procedures for MPAs have highlighted some important considerations often overlooked when analysing and interpreting results. These include a species' economic value, size and growth rate, time to maturity, habitat preference, depth range and behaviour (Claudet & Guidetti 2010, Claudet et al. 2010). Species with different life histories and ecological traits have been found to respond differently to reserve design and period of protection. For example, Claudet et al. (2010) found that period of protection strongly affected larger species but not small or medium-sized species. They attributed this difference to the longer period of time larger species often require to grow and mature. Another important consideration is the effect of habitat structure (Claudet & Guidetti 2010). MPAs often include complex and heterogeneous habitats, and the effect of these must be clearly separated from the effects of protection (García-Charton et al. 2004). Factors such as accessibility, population density and level of enforcement and compliance within an MPA will influence the effectiveness of the MPA (Lundquist & Granek 2005). The choice of sampling method and technique will also have a profound influence on the accuracy of the results and ecological questions answered (Thresher & Gunn 1986, Willis et al. 2000, Watson et al. 2010).

The Hawaiian Islands bottomfish fishery is the second most important fishery in Hawai'i and targets a multispecies group of deep-sea fish (down to 400 m) including snappers (Lutjanidae), jacks (Carangidae) and an endemic grouper, *Hyporthodus quernus* (Epinephelidae). Most of the commercially important species have a relatively high age at maturity, long life span and slow growth rate, making them particularly susceptible to overfishing (Ralston & Polovina 1982, Haight et al. 1993). In 1998, following a steady decline in bottomfish catch rates and evidence that the 2 commercially valuable species *Etelis carbunculus* and *E. coruscans* may be overfished, the State of Hawai'i Department of Land and Natural Resources implemented 19 Bottomfish Restricted Fishing Areas (BRFAs) throughout the main Hawaiian Islands (State of Hawai'i 2006). These BRFAs were designed to protect 20% of the essential fish habitat (EFH) for *E. carbunculus* and *E. coruscans* and to help replenish depleted bottomfish stocks by prohibiting bottom fishing within them, thus ensuring the long-term sustainability of the fishery (Parke 2007). EFH is defined as those waters and substrate necessary for fish

spawning, feeding or growth to maturity (Rosenberg et al. 2000). Currently, the EFH definition is one that encompasses the suite of targeted bottomfish species and is defined as 'all bottom waters between 0 and 400 m'. Submersible observations and fishing effort have demonstrated that adult bottomfish often associate with higher profile substrates and/or rocky substrates (Polovina et al. 1985, WPRFMC 1998, Kelley et al. 2006). These results have since been used to further constrain preferred adult bottomfish habitat to hard bottom between 100 and 400 m with a slope of  $>20^\circ$  (Kelley et al. 2006, Parke 2007). In 2005, with this increased understanding of bottomfish habitat requirements and the availability of multibeam and sidescan sonar mapping of the Hawaiian Islands, it was determined that only about 5% of this type of habitat occurred within the boundaries of the BRFAs (Parke 2007). In addition, the Pacific Islands Fisheries Science Centre (PIFSC) established that bottomfish continued to be overfished in the main Hawaiian Islands and that greater protection was necessary (Moffitt et al. 2006). This led to the implementation of additional bottom fishing restrictions including a 6 mo seasonal closure, reduced non-commercial bag limits, mandatory permits, vessel marking and a revised system of BRFAs that came into effect on June 1, 2007. The new system of BRFAs reduced the overall number of BRFAs to 12 but increased the area protected to include more bottomfish habitat. The present study presents fishery-independent data collected during the first year of implementation of the revised system of BRFAs as part of an ongoing monitoring program designed to assess the effectiveness of these BRFAs.

Evaluating the effectiveness of MPAs to protect targeted fish species requires careful choice of sampling technique and/or gear used to minimise potential biases (Willis & Babcock 2000, Watson et al. 2005). The chosen technique must be non-destructive, accurate and efficient (i.e. cost and time) but also appropriate for the species of interest and question being addressed (Thresher & Gunn 1986, Willis et al. 2000). Biases can include selectivity associated with the gear (e.g. gear attraction and avoidance, observer bias and size selectivity) or the biology or behaviour of the fish including size, detectability, habitat association and mobility (Willis et al. 2000, Watson et al. 2010). Most surveys of MPAs have used SCUBA-based underwater visual census (UVC) methods (Russ & Alcala 1996, Cappo et al. 2003). However, UVC is restricted by depths accessible to divers ( $<20$  m), may be affected by observer bias and can be unreliable for behaviourally adaptable spe-

cies (i.e. diver attraction and avoidance) (Cole 1994, Willis & Babcock 2000). Few non-destructive survey techniques are available to assess fish populations beyond the limits of diver-based UVCs. Some underwater visual surveys have been conducted using submersibles and remotely operated vehicles (Ralston et al. 1986, Adams et al. 1995, Trenkel et al. 2004). However, these techniques can be costly and time consuming and have produced variable and biased population density estimates as a result of avoidance or attraction to moving equipment and/or artificial lights (Ralston et al. 1986, Trenkel et al. 2004). Underwater 'video fishing' is an alternative non-destructive sampling technique developed to combine the advantages of underwater visual survey and extractive fishing techniques (e.g. selective trapping, hook and line fishing or trawling) (Willis & Babcock 2000, Willis et al. 2000, Cappo et al. 2003). While avoiding many of the biases and selectivity associated with alternative techniques, baited underwater video also has its limitations, including the reliance on good visibility and an unknown area sampled by the bait. Comparative research has demonstrated baited underwater video stations to provide a consistent and comparable method for assessing fish relative abundance (Willis et al. 2000, Cappo et al. 2004, Watson et al. 2005, Harvey et al. 2007). However, the distance over which fish may be attracted to the bait will remain unknown until the development of a robust method for modelling dispersal and distance of attraction to the bait (Priede & Merrett 1996, Harvey et al. 2007).

Much research has been undertaken to critically examine the biases and limitations of techniques assessing fish populations (e.g. Ralston et al. 1986, Thresher & Gunn 1986, Willis et al. 2000, Cappo et al. 2004, Watson et al. 2005). The major finding of this comparative research has been that different techniques can survey significantly different components of the fish fauna, and authors have cautioned researchers to choose a sampling technique that is appropriate for the species of interest (Willis et al. 2000, Cappo et al. 2004). For example, Cappo et al. (2004) compared baited remote underwater video stations (BRUVs) with prawn (shrimp) trawls and found that the trawls captured significantly more small, sedentary or cryptic species, while the BRUVs recorded a greater number of larger mobile species from a much wider size range of families. Watson et al. (2010) also established that BRUVs recorded a greater number of large-bodied targeted species in higher abundance when compared with diver-operated stereo video. Harvey et al. (2007) found the

number and diversity of fish to be greater and more consistent from baited versus unbaited video stations and, as a result, suggested that this technique may enable stronger statistical testing of the relative abundance of large predatory species in particular. For our research, it was decided that baited underwater video was the most appropriate and efficient non-destructive survey method for assessing targeted Hawaiian bottomfish. We used a baited stereo-video camera system, the bottom camera bait station (BotCam), designed specifically as a non-destructive fishery-independent tool for monitoring deepwater Hawaiian bottomfish and their habitat (Merritt et al. 2011). The advantage of stereo video over a single camera is the ability to make precise and accurate length measurements of fish to provide information on size-frequency distributions (Harvey & Shortis 1996, Harvey et al. 2002).

The focus of this research was to provide the first comprehensive fishery-independent baseline assessment of commercially important bottomfish populations within the main Hawaiian Islands across the revised system of BRFAs. Data collected during the first year after their implementation were evaluated to establish baseline bottomfish relative abundance and size-frequency distributions both inside and outside 6 of the 12 redefined BRFAs. The aim of the research was to test whether there was a significant difference in mean relative abundance or size of harvested species inside versus outside the BRFAs.

## MATERIALS AND METHODS

### Study site

The research was conducted across 6 of the 12 re-defined BRFAs within the main Hawaiian Islands (Fig. 1). In some instances, the original regions closed to bottom fishing in 1998 overlapped with the re-defined BRFAs implemented in 2007 offering continued protection, while closed areas not encompassed within 2007 areas became open to fishing in 2007. Two BRFAs were chosen to represent areas of continued closure (BRFA B, Ni'ihau and BRFA L, Hawai'i), 2 BRFAs were chosen because they were newly closed areas (BRFA D, west O'ahu and BRFA H, Pailolo Channel) and 2 represented BRFAs that encompassed smaller pre-existing closed areas (BRFA E, east O'ahu and BRFA F, Penguin Bank). Paired sampling was conducted inside and outside each of the BRFAs from May 2007 to July 2008 between depths of 100 and 300 m.

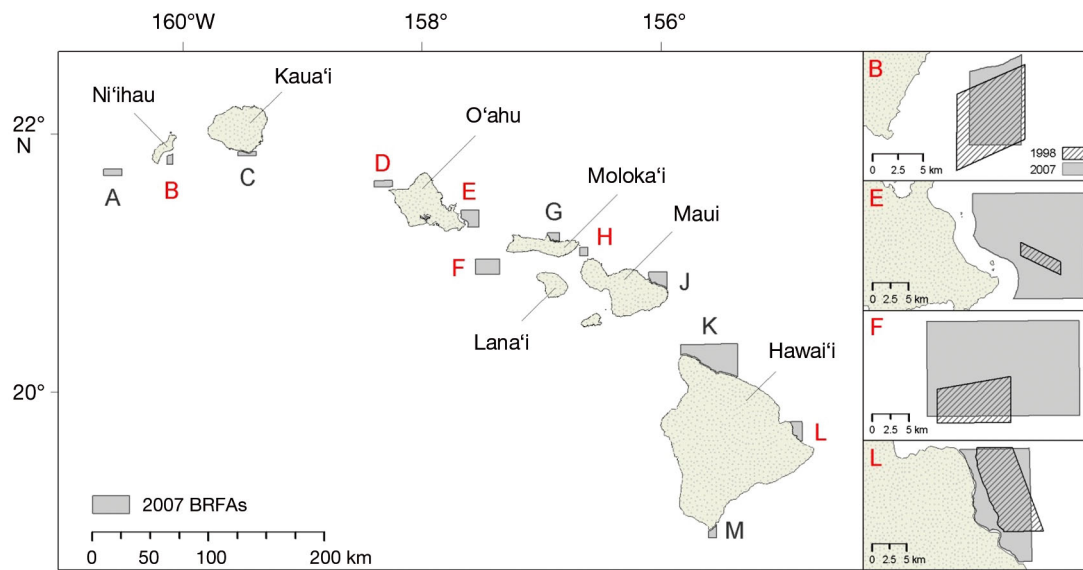


Fig. 1. Map of the main Hawaiian Islands showing location of revised Bottomfish Restricted Fishing Areas (BRFAs) implemented in 2007. Each BRFA has been coded by the State of Hawai'i with a letter, proceeding from west to east. BRFAs surveyed are indicated by red lettering. Inserted to the right are enlarged maps of the 2 ongoing BRFAs (B and L) and the 2 BRFAs encompassing smaller pre-existing closed areas (E and F). Diagonal hatching indicates location of old 1998 BRFAs

### Sampling technique

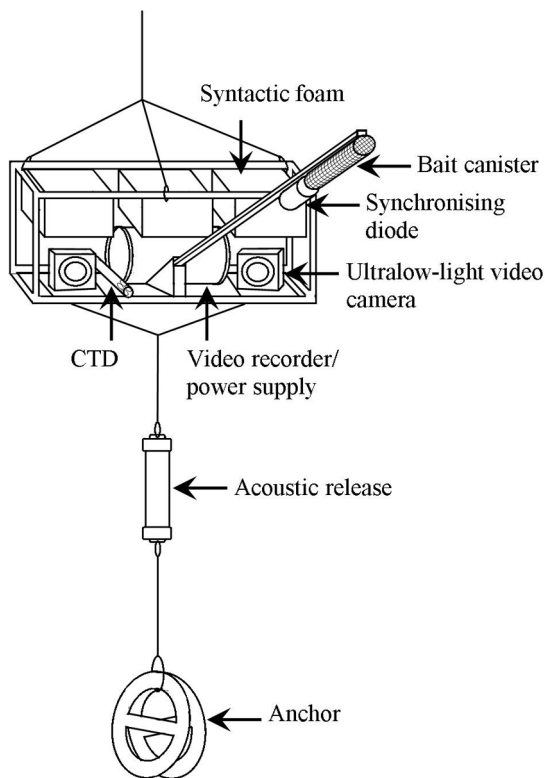


Fig. 2. Schematic of the bottom camera bait station (BotCam) used for assessing bottomfish relative abundance

The baited stereo-video camera system used in the present study was the BotCam developed by the NOAA PIFSC in collaboration with the Hawai'i Undersea Research Laboratory (Fig. 2). The BotCam was designed specifically as a fishery-independent tool for monitoring Hawaiian deepwater fish and their habitat after comparative research by Ellis & DeMartini (1995) found that baited video stations provided an accurate tool for sampling juvenile *Pristipomoides filamentosus*. Detailed information on the design of the system can be found in Merritt et al. (2011), who found the redesigned baited video system to be a flexible and economic tool for assessing these deepwater bottomfish. The system consists of 2 ultralow-light monochrome video cameras used to record under ambient light conditions to a depth of 300 m. Ambient lighting is preferred, as artificial lights have been noted to repel bottomfish species (Ralston et al. 1986). Sampling was completed between 08:00 and 16:00 h to avoid crepuscular changes in fish behaviour and maximise available ambient light at depth. Attached in front of the video cameras is a light diode used to synchronise the stereo-video pair, enabling accurate fish length measurements. Also attached is a plastic mesh bait canister. Bait consisted of approximately 800 g of

mixed chopped anchovy *Engraulis mordax* and market squid *Doryteuthis opalescens*, frozen to ensure it did not dissipate before reaching the seafloor. This bait was chosen to be consistent with that used by local bottom fishers. The system was moored to 2 anchor weights designed to rest on the seafloor, while syntactic foam blocks, attached to the camera frame, allowed the video cameras to float approximately 3 m off the bottom, optimising the field of view. The small footprint of the anchor allows the system to sit securely on high profile substrates, thus enabling it to record bottomfish in the steep and rugose terrain often favoured by these species. The system is retrieved via its surface-buoyed tether, the acoustic release used only if the anchor becomes lodged on the seafloor. Each system was deployed by boat and left to record on the seafloor for 45 min to optimise the number of fish observed with time (Harvey & Cappo 2001). Previous bait stations conducted from a submersible (Kelley & Ikehara 2006) found that 30 min was an adequate length of time to capture the peaking feeding activity stimulated by the bait (C. D. Kelley pers. comm.). To reduce the likelihood of an overlap in bait plumes and of sampling the same fish twice, concurrent deployed systems were placed a minimum of 400 m apart, with actual distances usually much greater (mean separation of  $1938 \pm 102$  m). Ellis & DeMartini (1995) estimated the greatest distance of attraction to bait over a 10 min period was between 48 to 90 m based on maximum recorded bottom current speeds of between  $0.1$  to  $0.2 \text{ m s}^{-1}$  and a swimming speed for *P. filamentosus* of  $0.6 \text{ m s}^{-1}$ . Based on this calculation, the greatest distance of attraction over a 45 min period would be between 250 and 408 m.

### Sampling design

Fish were sampled both inside and outside each of the redefined BRFA's using a stratified random sampling protocol recommended by the PIFSC and the University of Miami. Each BRFA location was designated 64 replicates, with 32 replicates inside the BRFA and 32 outside. The outside, unprotected area adjacent to each BRFA was an area equivalent to the bottomfish habitat inside the BRFA (100 to 300 m) on either side of the BRFA, following the bathymetric contours. Multibeam bathymetry and backscatter data, collected at a resolution of 20 m, were used to classify habitat into 4 categories: high or low profile

Table 1. Number of samples collected within each substrate category for each of the 6 Bottomfish Restricted Fishing Areas (BRFAs). High: high profile (slope  $\geq 20^\circ$ ); low: low profile (slope  $< 20^\circ$ )

BFRA	Location	Protection	Substrate				Total
			Reef		Sediment		
			High	Low	High	Low	
B	Ni'ihau	Yes	12	8	8	4	64
		No	12	8	8	4	
D	W. O'ahu	Yes	–	26	2	4	64
		No	12	8	8	4	
E	E. O'ahu	Yes	8	10	10	4	64
		No	12	8	8	4	
F	Penguin Bank	Yes	11	8	8	4	63
		No	12	8	8	4	
H	Pailolo Channel	Yes	–	27	–	4	62
		No	–	27	–	4	
L	Hawai'i	Yes	12	8	8	4	61
		No	9	8	8	4	

rocky substrates (hereafter called 'reef' for simplicity) and high or low profile sediment. The multibeam data were used to designate the substrate as either high profile (slope  $\geq 20^\circ$ ) or low profile (slope  $< 20^\circ$ ), while the backscatter data were used to designate the substrate as either reef (consolidated hard substrate) or sediment (unconsolidated soft substrate). Habitat was categorised at a resolution of  $200 \times 200$  m by assigning the habitat category comprising the majority of each  $200 \times 200$  m grid cell. BotCam deployments were randomly designated within each of these 4 habitat categories, with replicates weighted towards preferred bottomfish habitat to ensure greater replication where fish were expected to be found (detailed in Table 1). Where some habitat categories were not present, particularly at west O'ahu (D) and Pailolo Channel (H), additional replicates were allocated to the next most preferred bottomfish habitat as dictated by previous studies, which found that adult bottomfish often associate with rocky substrates and/or higher profile substrates (Polovina et al. 1985, WPRFMC 1998). The sampling protocol resulted in some differences in depths sampled, with the mean sample depth between each BRFA and its control site varying between 5 and 31 m.

### Image analysis

Video data were analysed to measure bottomfish relative abundance and size-frequency distribution. Relative abundance was quantified as the maximum



number (MaxN) of each species observed in a single frame during the entire 45 min video (Priede et al. 1994, Cappo et al. 2004). Individuals that could not be identified to species were identified at the highest taxonomic resolution possible. Schools of fish exceeding 50 individuals were rounded to the nearest increment of 5, with an exact number unrealistic with so many individuals moving in and around one another. Where individual fish were observed in both cameras, fork lengths were measured using 1 of 2 stereo-photogrammetric systems, initially Vision Measurement System (VMS) v.7.5 (Geometric Software) and then PhotoMeasure v.1.74 (SeaGIS), which replaced VMS. To avoid repeated measures of the same fish, measurements were made at a single time in the video where the relative abundance of the fish was maximised. Replicate measurements of each individual fish were taken where possible to increase precision and accuracy of the measurement. This was particularly important in this study, as the low light conditions affected the resolution of the video imagery and, in turn, the accuracy of length measurements. Any length measures with a residual parallax and a RMSE of >10 mm and a ratio of precision of measurement to length of fish of >10% were removed from the analysis.

Measurements were taken on average  $1.9 \pm 0.98$  m from the cameras, with a maximum distance of 8.2 m. The visual area sampled was noted to expand and contract due to the nature of working at these depths and changes in visibility. Based on these measurements and using minimum and maximum view distances 2 to 10 m from the cameras, the visual area sampled was estimated to be between 4 and 416 m<sup>2</sup>.

### Data analysis

Eight bottomfish species were examined: *Aphareus rutilans*, *Etelis carbunculus*, *E. coruscans*, *Hyporhamphus quernus*, *Pristipomoides filamentosus*, *P. sieboldii*, *P. zonatus* and *Seriola dumerili*. The first 7 species, locally referred to as the 'Deep 7', were chosen because they are the most commercially and recreationally valuable species. For simplicity, we refer to these 7 species as the 'Deep 7' throughout this paper. The eighth species, *S. dumerili*, was also included, as it was once a valuable component of the fishery and is now the most important bycatch species (WPRFMC 1998). Two of the Deep 7, *A. rutilans* and *P. zonatus*, were detected infrequently in very low relative abundances and could not be included in all statistical tests (species-specific permutational

multivariate ANOVA [PERMANOVA] or examination of length frequency, see below). A PERMANOVA (Anderson 2001) was chosen for the analyses, as the experimental design was unbalanced and the relative abundance of fish was highly skewed with many zero counts. The PERMANOVA was conducted for the Deep 7 assemblage and 6 of the 8 individual species using the PERMANOVA+ software in PRIMER 6 v.6.1.11, with the number of permutations set to 9999 (Anderson et al. 2008). The data were first fourth-root transformed to downweight the effect of large schools of fish recorded, and then the dissimilarity matrix was built using Bray-Curtis dissimilarities, which are appropriate for this type of ecological data (Bray & Curtis 1957). The sampling design consisted of 2 fixed and crossed factors: closure (2 levels) and substrate (4 levels). Paired sampling was conducted at the same time inside versus outside each BRFA to ensure that we controlled for time of year. However, the effect of BRFA location was not tested, as data were collected from each BRFA location at differing times during the year due to logistical constraints. Therefore, temporal changes in species distributions and relative abundances, such as species migratory patterns and spawning aggregations, could not be accounted for between BRFA locations.

Size-frequency distributions of individual species were tested using Kolmogorov-Smirnov tests to determine whether they differed inside versus outside the BRFAs. This test was only possible where >10 length measurements were available for a given species both inside and outside the BRFA. Significant differences in the size-frequency distributions inside versus outside the BRFAs are presented graphically. The Wilcoxon 2-sample test was used for smaller sample sizes ( $4 \leq n < 10$ ). This test is based on rank order and is appropriate for small sample sizes with unknown distributions (Wilcoxon 1945).

## RESULTS

### Relative abundance

Analysis using PERMANOVA, examining the effect of closure and substrate on harvested species, found no significant difference in relative abundance between open and closed areas for the Deep 7 assemblage or the 6 individual species (Table 2). However, several significant responses to substrate were detected for the Deep 7 assemblage and for some individual species. The Deep 7 had a significant response to substrate at the BRFAs E, F, H and L,

Table 2. Differences in relative abundance for the Deep 7 assemblage and individual harvested bottomfish species for each of the 6 Bottomfish Restricted Fishing Areas in response to the factors closure (C), substrate (S) and their interaction (C × S). E.: *Etelis*; H.: *Hyporthodus*; P.: *Pristipomoides*; S.: *Seriola*. \*0.05 > p > 0.01; \*\*0.01 > p > 0.001; \*\*\*p < 0.001

	B - Ni'ihau							D - west O'ahu						
	C (df = 1)		S (df = 3)		C × S (df = 3)		Error MS	C (df = 1)		S (df = 3)		C × S (df = 2) <sup>a</sup>		Error MS
	MS	F	MS	F	MS	F		MS	F	MS	F	MS	F	
<i>E. carbunculus</i>	36.1	0.77	52.6	1.13	52.6	1.13	46.7	37	0.5	59.7	0.8	72.5	0.97	74.7
<i>E. coruscans</i>	1.6	0.01	255.3	1.38	74.2	0.4	185.1	5.7	0.14	5.6	0.14	8.4	0.21	40.5
<i>H. quernus</i>	211.5	1.73	168.9	1.38	82.2	0.67	122.2	1.3	0.03	19.2	0.53	1.9	0.05	36.6
<i>P. filamentosus</i>	16.5	0.07	312.7	1.27	48.3	0.20	246.3	3.2	0.01	363.4	1.48	482.5	1.97	245.5
<i>P. sieboldii</i>	719.5	2.39	581.6	1.93	256.9	0.85	301.6	29.3	0.35	30.2	0.36	25.2	0.3	83.1
<i>S. dumerili</i>	0.46	0.00	359.0	1.14	124.0	0.39	315.7	4.4	0.02	205.1	0.88	364.4	1.56	233.7
Deep 7	1.57	1.12	2.46	1.74	0.96	0.68	1.41	0.15	0.23	0.52	0.80	0.71	0.10	0.64
	E - east O'ahu							F - Penguin Bank						
	C (df = 1)		S (df = 3)		C × S (df = 3)		Error MS	C (df = 1)		S (df = 3)		C × S (df = 3)		Error MS
	MS	F	MS	F	MS	F		MS	F	MS	F	MS	F	
<i>E. carbunculus</i>	299	2.29	22.4	0.17	34.9	0.27	130.7	5.6	0.02	571	1.85	435.3	1.41	308.8
<i>E. coruscans</i>	1.7	0.01	85.6	0.64	331.1	2.48	133.6	20.2	0.07	766.7	2.78*	115.3	0.42	276.1
<i>H. quernus</i>	67.7	1.33	87	1.71	87	1.71	51	6.6	0.12	55.9	1.04	9.4	0.17	53.9
<i>P. filamentosus</i>	64.4	0.18	1614	4.50**	262.3	0.73	359.1	1.2	0.00	276.2	0.67	264.2	0.64	410.1
<i>P. sieboldii</i>	218.4	1.49	117.9	0.8	20.9	0.14	146.6	36.3	0.12	1342	4.43**	1054	3.49*	302.2
<i>S. dumerili</i>	736.6	2.92	578.8	2.29	523.8	2.08	252.3	682.7	2.83	215.0	0.89	126.4	0.52	241.6
Deep 7	0.76	0.71	2.48	2.33*	0.85	0.80	1.06	0.17	0.08	4.26	2.08*	3.03	1.48	2.04
	H - Pailolo Channel							L - Hawai'i						
	C (df = 1)		S (df = 3)		C × S (df = 3)		Error MS	C (df = 1)		S (df = 3)		C × S (df = 3)		Error MS
	MS	F	MS	F	MS	F		MS	F	MS	F	MS	F	
<i>E. carbunculus</i>	140.3	0.43	5359	16.2***	140.3	0.43	329.5	0.4	0.002	472.9	2.19	436.2	2.02	216.3
<i>E. coruscans</i>	210.6	0.59	2029	5.72*	210.6	0.59	354.4	192.2	1.82	137.7	1.3	73.5	0.69	105.8
<i>H. quernus</i>	6.7	0.06	89.1	0.76	6.7	0.06	117.4	120.7	2.19	57.1	1.04	57.1	1.04	55.1
<i>P. filamentosus</i>	22.2	0.14	171.8	1.07	22.2	0.14	160.2	927.5	2.56	1412	3.89*	1154	3.18*	362.9
<i>P. sieboldii</i>	380.9	1.35	604.2	2.14	380.9	1.35	282.0	116.9	0.34	411.9	1.19	70.6	0.2	345.8
<i>S. dumerili</i>	0.36	0.00	178.7	0.77	583.7	2.51	232.5	435.2	2.88	49.5	0.33	9.0	0.06	151.1
Deep 7	1.06	0.65	9.89	6.07***	1.06	0.65	1.62	3.38	1.89	4.05	2.27*	2.32	1.30	1.78

<sup>a</sup>Term has one or more empty cells in the model

with pairwise comparisons establishing that there were significantly lower mean relative abundances detected over low profile sediments. Relative abundance over the remaining 3 substrate classes demonstrated an inconsistent preference for reef and/or high profile substrates (Fig. 3). Higher relative abundances of the Deep 7 assemblage were detected over reef and high profile substrates at BRFAs E and L, with significantly more over low profile reef than high profile sediment. In contrast, at BRFA F, while there were also higher relative abundances of the assemblage over reef and high profile substrates, there were significantly more over high profile sediment than low profile reef. Only 2 substrate categories were present and sampled at BRFA H. Here, significantly more Deep 7 species were found over low profile reef than low profile sediment. Deep 7 relative abundances were consistently low across all substrates at D, and relative abundances at BRFA B were highly variable, hence the difference between

high profile reef and low profile sediment having a low but insignificant p-value of 0.066.

Examination of individual species responses to substrate (Table 2) revealed that *Pristipomoides filamentosus* had significantly higher relative abundance over low profile reef at BRFA E. *Etelis coruscans* had a significantly higher relative abundance over high profile reef at BRFA F and low profile reef at H (where high profile reef habitat was absent). All *E. carbunculus* at BRFA H were found over low profile reef while being absent over low profile sediment. Significant interactions between closure and substrate were detected for *P. sieboldii* at BRFA F and for *P. filamentosus* at L. These responses mirror those found for the Deep 7 assemblage and suggest that *P. filamentosus* was driving the significant response to substrate in the Deep 7 assemblage at BRFAs E and L, with a preference for high and low profile reef. The same could be true for *E. carbunculus* and *P. sieboldii*, with these species potentially

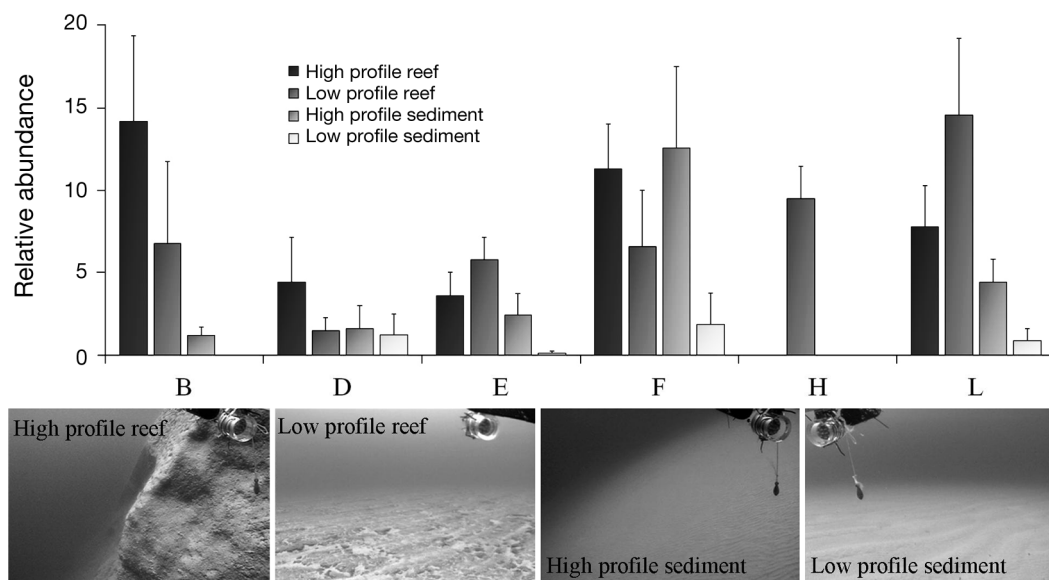


Fig. 3. Mean relative abundance (+1 SE) of deep 7 bottomfish species within each of the substrate categories from each of the 6 Bottomfish Restricted Fishing Areas (BRFAs): (see Fig. 1, Table 1). Note: Two substrate categories (high profile reef and high profile sediment) were absent from BRFA H. Example images, recorded by the bottom camera bait station (BotCam), are provided to illustrate the 4 substrate categories

driving the preference for high profile substrates, including both high profile reef and high profile sediment, at BRFA F. *E. carbunculus* and *E. coruscans* were possibly driving the preference for low profile reef at BRFA H.

Large variability in the relative abundance of the 8 species was observed across the 6 locations and between individual species (Fig. 4). This variability was related to the schooling behaviour of some of the species and their very patchy distribution. Large numbers (MaxN > 10) were recorded for 5 of the 8 harvested species; the exceptions were *Aphareus rutilans*, *Hyporthodus quernus* and *Pristipomoides zonatus*. The 2 largest individual schools were both recorded at B, with ~100 *P. sieboldii* recorded outside the BRFA and ~80 *Etelis coruscans* recorded inside the BRFA. When examining mean relative abundance, the largest MaxN and maximum prevalence (frequency of occurrence) across BRFA locations and between species, it was rare for these statistics to coincide (Fig. 4). Some general trends included some of the highest mean relative abundances and frequencies of occurrence inside the newly-closed BRFA H (i.e. *E. carbunculus*, *E. coruscans* and *P. filamentosus*) and some of the largest schools inside (*P. filamentosus* and *P. zonatus*) and outside (*A. rutilans* and *E. carbunculus*) the expanded BRFA F. In contrast, high mean relative abundance and high prevalence was recorded for several species outside the

ongoing BRFA L (i.e. *A. rutilans*, *P. filamentosus* and *P. zonatus*). In general, low relative abundance and prevalence was recorded for all species off BRFAs D and E. The exception, *Seriola dumerili*, was found to have the highest mean relative abundance and largest MaxN inside the expanded BRFA E.

### Size-frequency distributions

Statistical tests examining differences in the mean size (Wilcoxon test where  $n < 10$ ) or the size-frequency distribution (Kolmogorov-Smirnov test where  $n \geq 10$ ) of harvested species inside versus outside the BRFAs revealed some significant differences (Table 3; Fig. 5). *Pristipomoides filamentosus* and *Etelis coruscans* were both significantly larger inside BRFA B (Fig. 6). The mean fork lengths of *P. filamentosus* and *E. coruscans* inside the BRFA were 97.4 mm and 83.3 mm larger, respectively, than the mean fork length outside the BRFA. Individual *P. filamentosus* measured inside the BRFA were between 560 and 785 mm, while individuals outside the BRFA were between 464 and 679 mm. *E. coruscans* inside the BRFA were between 576 and 911 mm, while those outside the BRFA were between 574 and 825 mm. *P. sieboldii* was also found to have a significantly larger size-frequency distribution within BRFAs F and H. The mean fork



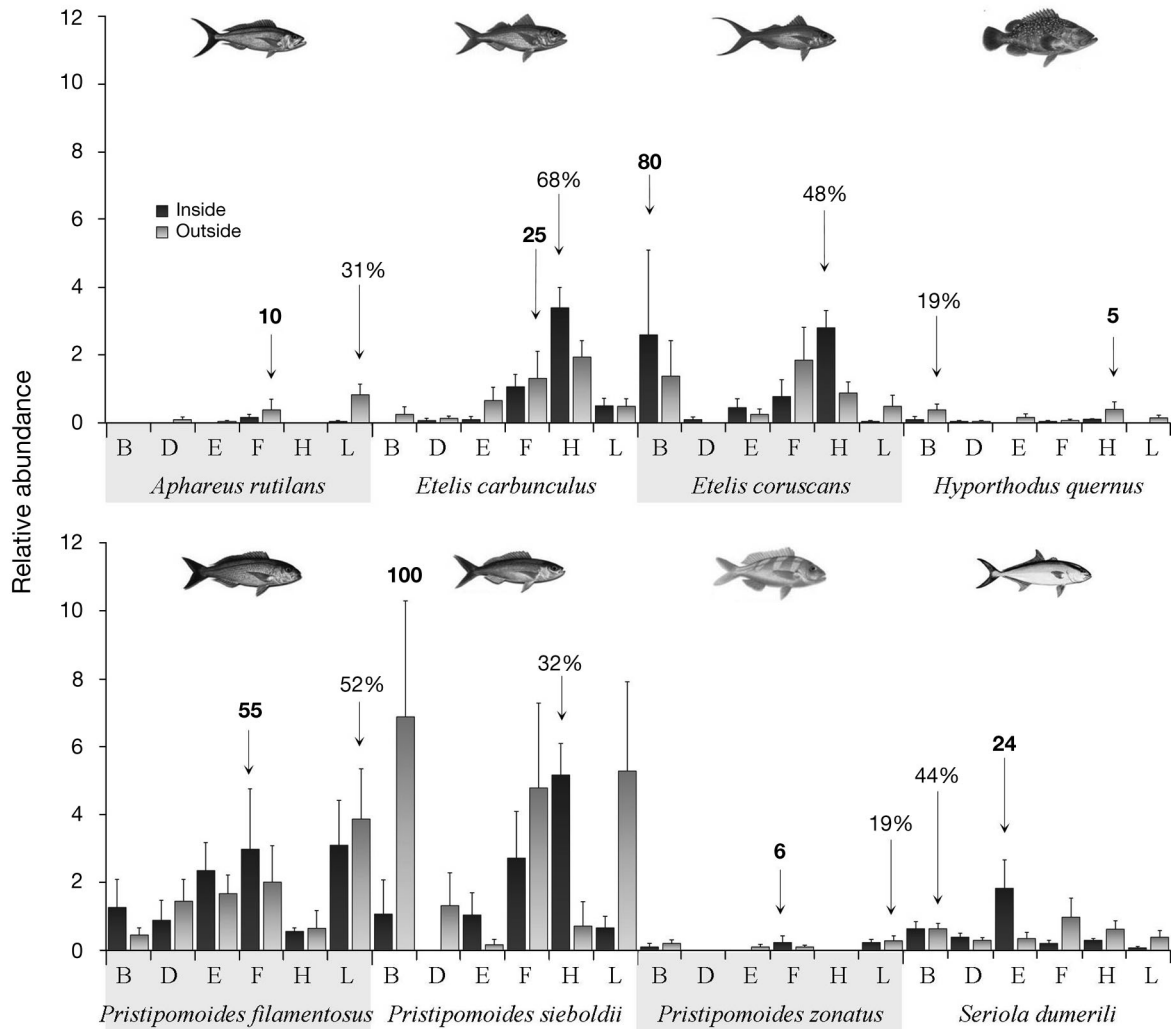


Fig. 4. Mean relative abundance (+1 SE) of harvested bottomfish species recorded inside and outside the 6 BRFAs (see Fig. 1, Table 1). Maximum relative abundance for each species is shown in **bold**, and percentages indicate maximum prevalence (percent of sites where species were recorded). Illustrations by Les Hata©, Hawaii Department of Land and Natural Resources

lengths of *P. sieboldii* inside the BRFAs were 111 mm larger in F and 79.7 mm larger in H than outside both BRFAs. *Seriola dumerili* were significantly larger within BRFA H, with a mean fork length 330.2 mm larger outside the BRFA. However, only 6 *S. dumerili* were measured within H.

A few species were found to have significantly larger individuals outside the BRFAs (Table 3; Fig. 5). The size-frequency distribution of *Pristipomoides filamentosus* at BRFA D revealed a distinctive split in the size distribution, with mostly juveniles within the BRFA and adults outside the BRFA (Fig. 6). *Etelis carbunculus* had a significantly larger size-frequency distribution outside BRFA H. Individuals outside H tended to be larger, in contrast a more even size-frequency distribution with equal representation of

small, intermediate and larger individuals within H (Fig. 6). No species were found to have significantly larger size-frequency distributions within BRFA L, however, *P. filamentosus* and *P. sieboldii* were both found to be significantly larger (82.9 and 73.3 mm, respectively) outside L.

## DISCUSSION

The present study found no increases in the relative abundance of Hawaiian bottomfish inside the 6 redefined BRFAs across the main Hawaiian Islands. This was as expected for the newly-established BRFAs and those BRFAs where a small fraction of the area had been previously protected. However, evalu-

Table 3. Mean fork length (mm) of harvested bottomfish species sampled within and outside the Bottomfish Restricted Fishing Areas (BRFAs). These were calculated using the Wilcoxon test (W) for small sample sizes or the Kolmogorov-Smirnov test (D) where 10 or more fish measures were available both inside and outside the BRFA. Values in **bold** are significant ( $<0.05$ ); –: not tested as too few measurements

Species	Inside	Outside Mean $\pm$ SE (n)	Statistic W	D	p	Inside	Outside Mean $\pm$ SE (n)	Statistic W	D	p
<b>B - Ni'ihau</b>										
<i>E. carbunculus</i>	–	389.6 $\pm$ 25.5 (3)	–	–	–	349.0 $\pm$ 7.4 (2)	397.2 $\pm$ 23.8 (3)	–	–	–
<i>E. coruscans</i>	763.6 $\pm$ 24.2 (19)	680.3 $\pm$ 14.6 (23)	–	0.450	<b>&lt;0.05</b>	546.9 $\pm$ 57.7 (3)	–	–	–	–
<i>H. quernus</i>	619.6 $\pm$ 34.6 (2)	752.5 $\pm$ 56.6 (6)	–	–	–	423.3 $\pm$ 0.0 (1)	481.6 $\pm$ 0.0 (1)	–	–	–
<i>P. filamentosus</i>	662.0 $\pm$ 12.1 (19)	564.6 $\pm$ 21.9 (12)	–	0.600	<b>&lt;0.01</b>	459.7 $\pm$ 27.3 (17)	546.5 $\pm$ 17.4 (21)	0.570	<b>&lt;0.01</b>	–
<i>P. sieboldii</i>	355.2 $\pm$ 7.7 (14)	340.7 $\pm$ 5.1 (66)	–	0.240	0.45	–	236.4 $\pm$ 4.2 (29)	–	–	–
<i>Seriola dumerili</i>	797.2 $\pm$ 36.0 (15)	815.2 $\pm$ 37.6 (17)	–	0.320	0.317	710.2 $\pm$ 95.9 (8)	889.3 $\pm$ 94.6 (6)	52	–	0.414
<b>F - Penguin Bank</b>										
<i>E. carbunculus</i>	302.3 $\pm$ 25.1 (2)	404.1 $\pm$ 38.0 (7)	–	–	–	375.6 $\pm$ 15.6 (15)	386.8 $\pm$ 20.8 (19)	–	0.180	0.926
<i>E. coruscans</i>	599.6 $\pm$ 67.2 (6)	549.0 $\pm$ 0.0 (1)	–	–	–	634.2 $\pm$ 53.8 (4)	654.0 $\pm$ 25.0 (18)	42	–	0.770
<i>H. quernus</i>	–	472.0 $\pm$ 28.7 (2)	–	–	–	–	572.3 $\pm$ 138.1 (2)	–	–	–
<i>P. filamentosus</i>	403.2 $\pm$ 11.0 (43)	426.2 $\pm$ 15.7 (34)	0.153	0.728	404.8 $\pm$ 13.2 (54)	446.2 $\pm$ 24.2 (27)	–	–	–	–
<i>P. sieboldii</i>	367.8 $\pm$ 14.3 (5)	–	–	–	–	331.8 $\pm$ 4.3 (58)	220.8 $\pm$ 6.8 (44)	0.190	0.524	<b>&lt;0.001</b>
<i>S. dumerili</i>	623.4 $\pm$ 14.3 (46)	723.3 $\pm$ 42.0 (8)	311	–	<b>&lt;0.05</b>	587.3 $\pm$ 90.5 (3)	690.4 $\pm$ 21.7 (26)	–	0.900	–
<b>L - Hawai'i</b>										
<i>E. carbunculus</i>	388.4 $\pm$ 10.1 (63)	446.6 $\pm$ 15.1 (24)	–	0.381	<b>&lt;0.01</b>	380.9 $\pm$ 25.0 (11)	325.5 $\pm$ 19.4 (8)	61	–	0.127
<i>E. coruscans</i>	405.3 $\pm$ 16.2 (27)	332.8 $\pm$ 44.1 (11)	–	0.364	0.198	499.4 $\pm$ 0.0 (1)	705.4 $\pm$ 37.1 (9)	–	–	–
<i>H. quernus</i>	775.4 $\pm$ 210.7 (2)	613.0 $\pm$ 21.2 (5)	–	–	–	–	652.4 $\pm$ 31.4 (4)	–	–	–
<i>P. filamentosus</i>	489.1 $\pm$ 18.2 (7)	491.7 $\pm$ 28.6 (9)	64	–	0.681	249.5 $\pm$ 5.3 (86)	322.4 $\pm$ 13.3 (74)	–	0.420	<b>&lt;0.001</b>
<i>P. sieboldii</i>	245.2 $\pm$ 9.5 (30)	165.5 $\pm$ 6.6 (7)	33	–	<b>&lt;0.001</b>	218.8 $\pm$ 12.9 (12)	292.1 $\pm$ 5.5 (70)	–	0.730	<b>&lt;0.001</b>
<i>S. dumerili</i>	952.7 $\pm$ 78.4 (6)	622.5 $\pm$ 15.7 (16)	110	–	<b>&lt;0.01</b>	900.1 $\pm$ 0.0 (1)	949.0 $\pm$ 46.6 (11)	–	–	–

ation of size-frequency distributions revealed that the 2 most commercially valuable species, *Etelis coruscans* and *Pristipomoides filamentosus*, were significantly larger inside the ongoing BRFA B. When comparing the 97.4 mm increase in average size of *P. filamentosus* with age and growth information taken from Andrews et al. (2011), the larger fish inside BRFA B are estimated to be approximately 10 yr older than those in neighbouring unprotected areas. While we have no data from when before the BRFAs were declared and therefore cannot make any firm conclusions, this increase in size corresponds well with a 10 yr restriction on bottom fishing.

One key question managers of MPAs want answered is the time required for an MPA to be effective. For targeted species, managers need information on recovery rates i.e. how long will it take to see an increase in the target species' abundance and size? While some studies have detected increases in fish size and density in just 1 to 3 yr after protection (Roberts 1995, Halpern & Warner 2002), others have demonstrated that these results may take decades (Jennings 2000, Micheli et al. 2004, Russ & Alcala 2004). Differences, including size and age at sexual maturity, reproductive biology, diet, mobility and behavior, will all have a profound influence on how a species responds to protection and when these responses become apparent (Willis et al. 2003, Berkeley et al. 2004, Russ & Alcala 2004, Claudet et al. 2010). As the majority of the Hawaiian bottomfish species have a relatively high age at maturity, long life span and slow growth rate, it follows that it will be some time for changes to take effect (Ralston & Polovina 1982, Haight et al. 1993). For example, *Etelis coruscans*, *Hypporthodus quernus* and *Pristipomoides sieboldii* are particularly slow growing and slow to mature, taking an estimated 6 or more years to reach maturity (Everson et al. 1989, Williams

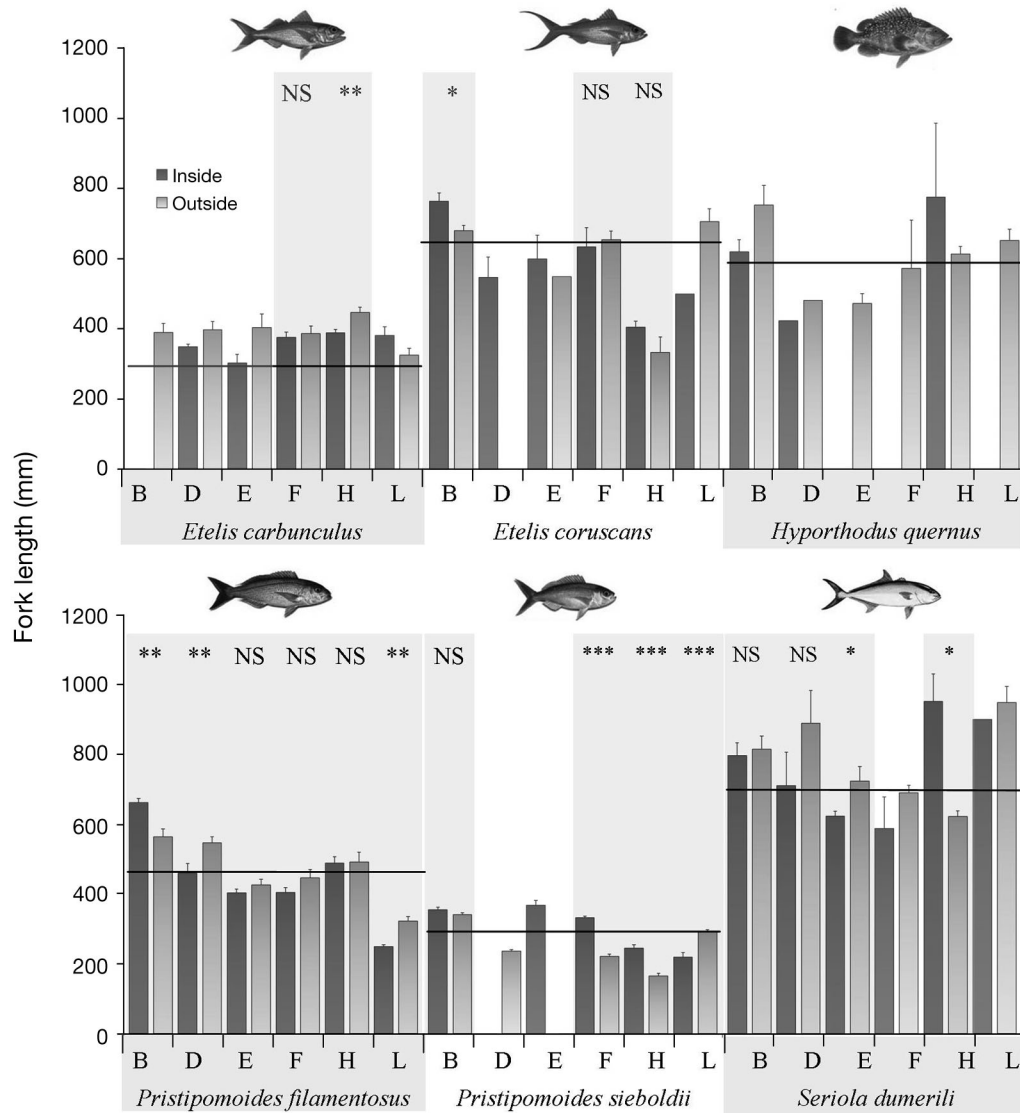


Fig. 5. Mean fork length (+1 SE) of harvested bottomfish species recorded inside and outside the 6 Bottomfish Restricted Fishing Areas (BRFAs) (see Fig. 1, Table 1). Test results are shown for significant differences in size-frequency distributions, calculated using the Wilcoxon test for small sample sizes or the Kolmogorov-Smirnov test where 10 or more fish measures were available both inside and outside the BRFA. Those species and sites that could be tested ( $n \geq 4$  both inside and outside the protected area) are indicated by grey shading. Horizontal lines indicate  $L_{50}$ , the reported size (length) at which 50% of the population is sexually mature (Kikkawa & Everson 1984, Everson et al. 1989, DeMartini & Lau 1999, Harris et al. 2007, DeMartini et al. 2011). Illustrations by Les Hata©, Hawaii Department of Land and Natural Resources. NS: not significant; \* $0.05 > p > 0.01$ ; \*\* $0.01 > p > 0.001$ ; \*\*\* $p < 0.001$

& Lowe 1997, DeMartini et al. 2011). In addition, *H. quernus* is a protogynous hermaphrodite (DeMartini et al. 2011). Therefore, while females mature at 58 cm total length (TL) or 6 to 7 yr, changing sex from female to male occurs at 89 to 90 cm TL, which is broadly estimated to be at more than 20 yr of age (DeMartini et al. 2011). Overfishing of this species could result in changes in the sex ratio, sperm limitation or a reduced size or age at maturity (Alonzo & Mangel 2004, Molloy et al. 2007). For such a long-

lived species with such a high age at maturity, it is not difficult to see how it may be decades before an effect of protection is detected. These life history traits combined with the results for *P. filamentosus* and *E. coruscans* inside the ongoing BRFA B suggest very slow recovery rates for Hawaiian bottomfish species. This is an important outcome for managers as it highlights the need to ensure the long-term protection and management for species demonstrating low rates of recovery.

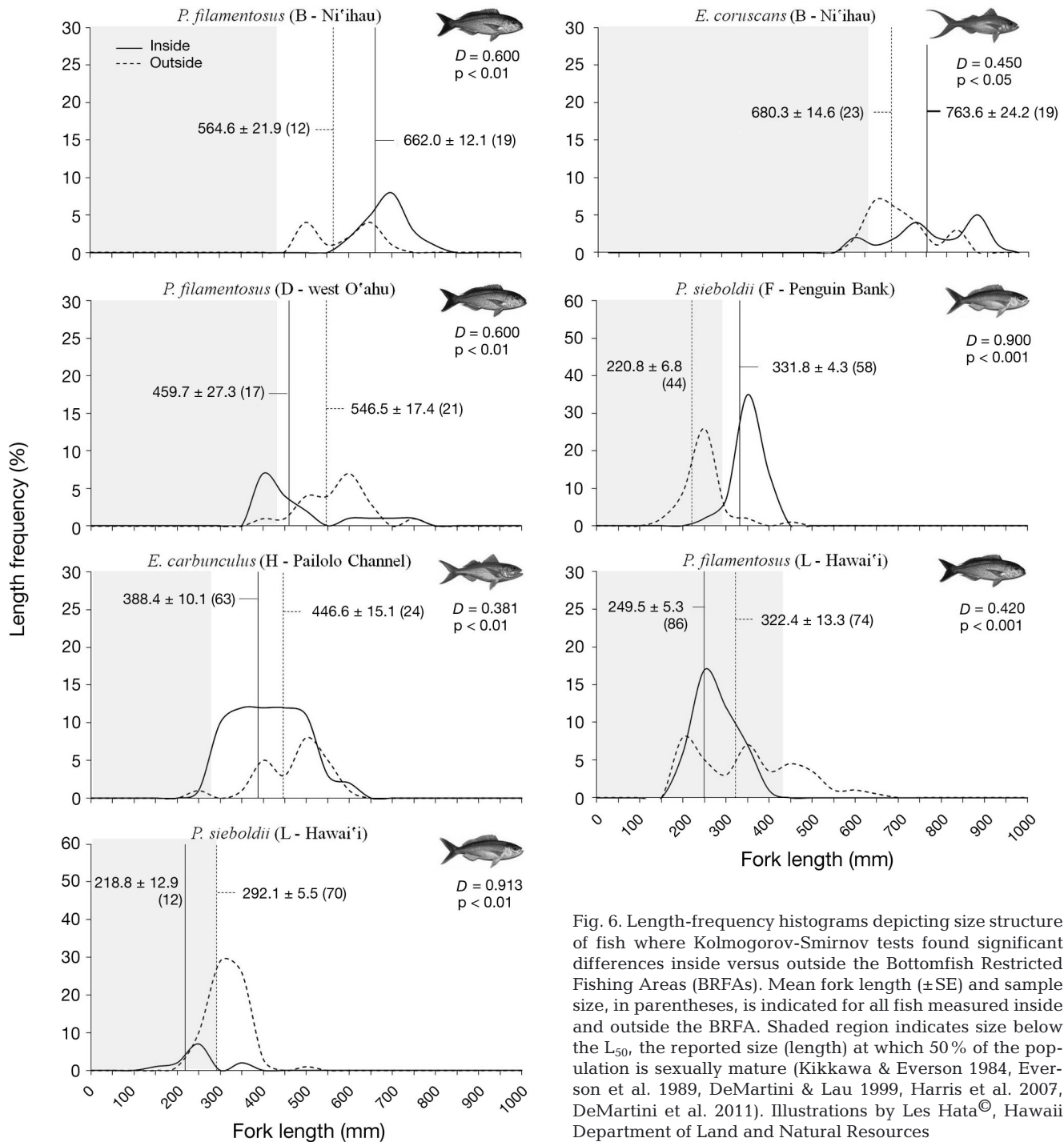


Fig. 6. Length-frequency histograms depicting size structure of fish where Kolmogorov-Smirnov tests found significant differences inside versus outside the Bottomfish Restricted Fishing Areas (BRFAs). Mean fork length ( $\pm$  SE) and sample size, in parentheses, is indicated for all fish measured inside and outside the BRFA. Shaded region indicates size below the  $L_{50}$ , the reported size (length) at which 50% of the population is sexually mature (Kikkawa & Everson 1984, Everson et al. 1989, DeMartini & Lau 1999, Harris et al. 2007, DeMartini et al. 2011). Illustrations by Les Hata<sup>©</sup>, Hawaii Department of Land and Natural Resources

While most of the harvested bottomfish species are long lived and slow to mature, there are some notable exceptions. For example, *Seriola dumerili* reaches sexual maturity in as little as 1.3 yr and at the largest size of any species, indicating an extremely fast growth rate (Uchida & Uchiyama 1986, Harris et al. 2007). It may follow that this species should be the first to be detected in higher abundance and greater

size within the ongoing BRFAs. However, this was not the case, with few differences detected in abundance and size of this species. This result could be attributed both to its high mobility and to sociological influences (Uchida & Uchiyama 1986). Generally, MPAs have not been considered effective at enhancing densities of highly mobile species, as migratory species with home ranges larger than the size of the

MPA will not be fully protected. However, recent reviews by Palumbi (2004) and Claudet et al. (2010) found evidence that protection can benefit very vagile benthic, benthic-pelagic and pelagic commercially exploited species. A suggested mechanism for this response is that protection also increases habitat quality and densities of prey species, thereby attracting and retaining highly mobile species within MPAs (Rodwell et al. 2003). In addition, there is growing recognition that while these reserves may not be protecting highly mobile species 100% of the time, they are still offering a potential reduction in fishing mortality (DeMartini 1993, Palumbi 2001). This reduction in fishing mortality is proportional to the time spent within MPAs, which is, in turn, proportional to the percent of the species distribution that is protected. It is therefore hypothesised that positive effects will be seen for a species where a comprehensive network of MPAs is protecting a significant portion of its distribution (DeMartini 1993, Palumbi 2001). A second consideration when interpreting the response of *S. dumerili* is its change in status in the commercial catch. In the past, *S. dumerili* was an important component of the bottomfish fishery in Hawai'i. However, it is currently the least valuable of the captured species, and for the past few decades landings have dropped significantly, with it now appearing as bycatch in catch reports. This change has been attributed to its association with ciguatera poisoning and a resulting ban on commercial sales (Kikkawa & Everson 1984, Uchida & Uchiyama 1986). Therefore, in addition to the species' biological characteristics, changes in fishing priorities will also influence the detected responses to the BRFAs and how we interpret those responses.

While some potentially promising responses to protection were detected for BRFA B, quite the opposite was recorded for BRFA L, the second ongoing BRFA. Here, 2 harvested species (*Pristipomoides filamentosus* and *P. sieboldii*) were significantly larger outside the BRFA. In addition, all of the 74 individual *P. filamentosus* measured inside the BRFA were too small to be sexually mature, as was the single *Etelis coruscans* recorded inside the BRFA. Again, no data were collected before this BRFA was declared, but these are not the results expected after 10 yr of protection. In this situation, it is particularly important to examine other potentially confounding factors. In contrast to BRFA B located off the most remote of the main Hawaiian Islands, BRFA L is located next to the second largest port in Hawai'i, Hilo, offering easier access, higher population pressure and more problematic enforcement with few resources available to

ensure compliance. Sites assessed outside BRFA L to the south towards Kumakahe Point have limited accessibility. This rocky, cliff-lined coast has no ports and faces northeast, directly into the prevailing trade winds. Recent studies have now documented strong correlations between accessibility and proximity to population centres and reductions in top predator abundance and size and include studies from Hawaii (Friedlander & DeMartini 2002, Williams et al. 2008).

In addition to considering accessibility, when BRFA L was originally declared in 1998, a large portion of preferred bottomfish habitat was not included. The major habitat within this BRFA is a coastal terrace extending along its length. Originally, only the deepest sections of this terrace (approximately 200 to 400 m) were included in the BRFA, with the shallower sections (<200 m) open to fishing. This shallow terrace section has since been closed to fishing with the implementation of the revised system of BRFAs in 2007. Having the shallower section remain open to fishing is likely to have had a profound influence on bottomfish populations and on *Pristipomoides filamentosus* in particular. Research by Merritt et al. (2011), using the same BotCam as that used in this research, examined the distribution and relative abundance of *Etelis coruscans* and *P. filamentosus* between 100 to 300 m depth in BRFA F. They established that *E. coruscans* was primarily restricted to depths of >200 m, whereas *P. filamentosus* was restricted to depths of <250 m. Research by Ralston et al. (1986), using observations from submersible dives off Johnston Atoll (1250 km southwest of O'ahu), also reported the depth range of *P. filamentosus* to be shallower (120 to 260 m) than that of *E. coruscans* (250 to 355 m). Therefore, it follows that while the original BRFA should have been providing protection for *E. coruscans*, it is unlikely to have offered the same protection for *P. filamentosus*. While it is possible that other ecological and environmental factors such as competition, habitat quality, oceanographic processes and productivity may be influencing the distribution of *P. filamentosus*, overfishing is also likely to explain why no adult *P. filamentosus* and *E. coruscans* were recorded within BRFA L. Establishing exactly what is driving these differences will require ongoing monitoring and more detailed information on species-specific habitat and ecological requirements, in conjunction with a formal assessment of enforcement.

Hawaiian bottomfish are known to have strong habitat associations. Larger species are reported to form large aggregations near high relief features, and smaller species are found near hard substrates



with high structural complexity (Ralston et al. 1986, Kelley et al. 2006, Parke 2007, Merritt et al. 2011). Some significant effects of habitat were detected for both the Deep 7 assemblage and for a few individual species. However, the effects were inconsistent between research locations and between species. While the Deep 7 were found in significantly lower mean relative abundances over low profile sediment, relative abundances over the remaining substrate classes demonstrated an inconsistent preference for reef and/or high profile substrates. This differs from our current understanding that Hawaiian bottomfish species are affiliated with hard, high profile substrates (Parke 2007). For example, *Pristipomoides filamentosus* was found to prefer reef including high and low profile reef at both BRFA E and L, while *Etelis coruscans* showed a preference for high profile substrates including high profile reef and high profile sediment at BRFA F. The results suggest that the species are responding to their habitat in a more complex manner than previously thought and that there are species-specific differences in habitat preferences. The habitat classification used was quite broad, with substrate classified into 4 categories based on the dominant substrate within a 200 × 200 m grid. While more detailed and fine-scale information on species–habitat associations would be very useful, in the absence of a robust model of the area of attraction to the bait, the classification of habitat at this scale was more appropriate. Based on the calculations by Ellis & DeMartini (1995), if a video station is set in high currents, it is possible that individuals could be attracted from a maximum distance of between 250 and 408 m. This means that some stations set in high current may have also sampled an adjacent grid possibly dominated by a different substrate type. While not affecting our assessment of protection, as samples were placed a minimum of 400 m apart, this is something that needs to be addressed to enable us to obtain a clearer picture of bottomfish habitat associations. Having a solid understanding of species-specific habitat preferences would allow us to better understand the amount and quality of bottomfish habitat offered by each of the BRFA's. This understanding would, in turn, provide insight into the contribution that individual BRFA's provide for protecting Hawaiian bottomfish and the overall contribution that the network of BRFA's will make for protecting Hawaiian bottomfish populations.

A final consideration is the sampling technique. Many studies have demonstrated bias and selectivity among sampling methods used to assess fish popula-

tions (Thresher & Gunn 1986, Willis et al. 2000, Trenkel et al. 2004), with comparative research suggesting that no single technique will provide information on all fish species (Cappo et al. 2004, Watson et al. 2010). Instead, authors recommend careful choice of sampling method to suit the species of interest and question being addressed (Thresher & Gunn 1986, Willis et al. 2000). Stereo-baited underwater video was chosen for this research as it has been demonstrated to provide a more effective and efficient means for sampling larger mobile target species (Cappo et al. 2004, Harvey et al. 2007, Watson et al. 2010). Video-based techniques have been increasingly used to monitor MPAs as they are non-destructive, cost effective, not limited by depth and remove some major sources of bias, including observer bias and diver attraction or avoidance (see Cappo et al. 2003 for review, Willis & Babcock 2000, Willis et al. 2000). Most video systems are baited as data collected using unbaited systems can be very sparse, with much greater replication and field effort required to provide statistically testable results (Harvey et al. 2007). However, one of the key issues yet to be addressed is the effect of using bait on fish behaviour and on the distance over which fish are attracted. Some studies have attempted to model the area of attraction using current velocity, fish swimming speed and models of bait plume behaviour (e.g. Priede & Merrett 1996). However, these models currently require some unverifiable assumptions. The research by Harvey et al. (2007) comparing baited versus unbaited underwater video stations conceded that fish behaviour (e.g. swimming speed, schooling behaviour, levels of curiosity and aggression) and life history (e.g. reproduction, feeding ecology, mobility and home range) do presumably affect attraction to the bait. However, they still found baited underwater video stations able to collect robust and reproducible data. They found that variances of individual species sampled within habitats decreased when using bait, which was noted as particularly important for larger, more mobile species with relatively low densities and patchy distributions. We addressed the problem of an unknown area sampled by the bait by using a relatively short soak time (45 min) and adequate separation between samples to avoid overlap of the bait plume and ensure that samples were independent of one another (Ellis & DeMartini 1995, Cappo et al. 2004). The development of an accurate model of the area of attraction to the bait would enable us to take these results one step further to establish bottomfish abundance (number of fish per unit area) and more detailed habitat affiliations.

## CONCLUSIONS

From this first comprehensive fishery-independent assessment, we have robust baseline data on commercially important bottomfish populations across the main Hawaiian Islands. Few significant differences were detected from this first assessment. However, differences detected in size-frequency distributions inside BRFA B (ongoing BRFA) provide evidence for very slow recovery rates for these deep-water species, which is consistent with their known life histories. Our results suggest that differences in size-frequency distributions can be detected after 10 yr but that it will take more years, possibly decades, before we detect large changes in species abundances. Having established the value of solid size-frequency distribution data, sampling intensity will be increased in future assessments to increase the number of length measurements for all harvested species. Another consideration is a better understanding of species-specific habitat requirements, both to ensure that high-quality bottomfish habitat is included within the BRFAs and to strengthen our sampling and statistical analyses. Individually, each BRFA is providing a unique set of habitat characteristics and environmental conditions affecting the distribution and relative abundance of bottomfish. Future research must examine the effect that the whole network of BRFAs is having on bottomfish populations across the main Hawaiian Islands. Differences in accessibility and proximity to population centres are likely to influence levels of enforcement and compliance. It is highly recommended that this be formally assessed to obtain a full picture of whether or not these BRFAs are achieving their purpose. While no data were collected on bottomfish populations before implementation of the system of BRFAs, this research has provided comprehensive baseline data on targeted bottomfish populations and some valuable information on expected recovery rates. This is just a first step, and only with ongoing monitoring and research will a full understanding of Hawaiian bottomfish populations and recovery rates be achieved.

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## LITERATURE CITED

- Adams PB, Butler JL, Baxter CH, Laidig TE, Dahlin KA, Wakefield WW (1995) Population estimates of Pacific coast groundfishes from video transects and swept-area trawls. *Fish Bull* 93:446–455
- Alonzo SH, Mangel M (2004) The effects of size-selective fisheries on the stock dynamics of and sperm limitation in sex-changing fish. *Fish Bull* 102:1–13
- Anderson MJ (2001) A new method for non-parametric multivariate analysis of variance. *Austral Ecol* 26:32–46
- Anderson MJ, Gorley RN, Clarke KR (2008) PERMANOVA+ for PRIMER: guide to software and statistical methods. PRIMER-E, Plymouth
- Andrews AH, Humphreys RL, DeMartini E, Nichols RS, Brodziak J (2011) Bomb radiocarbon and lead-radium dating of opakapaka (*Pristipomoides filamentosus*) Admin Rep H-11-04, Pacific Islands Fish Sci Cent, Natl Mar Fish Serv, NOAA, Honolulu, HI
- Berkeley SA, Hixon MA, Larson RJ, Love MS (2004) Fisheries sustainability via protection of age structure and spatial distribution of fish populations. *Fisheries* 29: 23–32
- Bray JR, Curtis JT (1957) An ordination of the upland forest communities of southern Wisconsin. *Ecol Monogr* 27: 325–349
- Cappo M, Harvey E, Malcolm H, Speare P (2003) Potential of video techniques to monitor diversity, abundance and size of fish in studies of marine protected areas. In: Beumer JP, Grant A, Smith DC (eds) *Aquatic protected areas—What works best and how do we know?* Proc World Congr Aquat Protected Areas. Australian Society for Fish Biology, North Beach, p 455–464
- Cappo M, Speare P, De'ath G (2004) Comparison of baited remote underwater video stations (BRUVS) and prawn (shrimp) trawls for assessments of fish biodiversity in inter-reefal areas of the Great Barrier Reef Marine Park. *J Exp Mar Biol Ecol* 302:123–152
- Claudet J, Guidetti P (2010) Improving assessments of marine protected areas. *Aquat Conserv* 20:239–242
- Claudet J, Osenberg CW, Domenici P, Badalamenti F and others (2010) Marine reserves: fish life history and ecological traits matter. *Ecol Appl* 20:830–839
- Cole RG (1994) Abundance, size structure, and diver-oriented behaviour of three large benthic carnivorous fishes in a marine reserve in northeastern New Zealand. *Biol Conserv* 70:93–99
- DeMartini EE (1993) Modeling the potential of fishery reserves for managing Pacific coral reef fishes. *Fish Bull* 91:414–427
- DeMartini EE, Lau BB (1999) Morphometric criteria for esti-

- mating sexual maturity in two snappers, *Etelis carbunculus* and *Pristipomoides sieboldii*. Fish Bull 97:449–458
- DeMartini EE, Everson AR, Nichols RS (2011) Estimates of body sizes at maturation and at sex change, and the spawning seasonality and sex ratio of the endemic Hawaiian grouper (*Hypporthodus quernus*, F. Epinephelidae). Fish Bull 109:123–134
- Ellis DM, DeMartini EE (1995) Evaluation of a video camera technique for indexing abundances of juvenile pink snapper, *Pristipomoides filamentosus*, and other Hawaiian insular shelf fishes. Fish Bull 93:67–77
- Everson AR, Williams HA, Ito BM (1989) Maturation and reproduction in two Hawaiian eteline snappers, uku, *Aprion virescens*, and onaga, *Etelis coruscans*. Fish Bull 87:877–888
- Friedlander AM, DeMartini EE (2002) Contrast in density, size and biomass of reef fishes between the northwestern and the main Hawaiian Islands: the effect of fishing down apex predators. Mar Ecol Prog Ser 230:253–264
- García-Charton JA, Pérez-Ruzafa Á, Sánchez-Jerez P, Bayle-Sempere JT, Reñones O, Moreno D (2004) Multi-scale spatial heterogeneity, habitat structure, and the effect of marine reserves on Western Mediterranean rocky reef fish assemblages. Mar Biol 144:161–182
- Green BS (2008) Maternal effects in fish populations. Adv Mar Biol 54:1–105
- Haight WR, Kobayashi DR, Kawamoto KE (1993) Biology and management of deepwater snappers of the Hawaiian Archipelago. Mar Fish Rev 55:20–27
- Halpern BS, Warner RR (2002) Marine reserves have rapid and lasting effects. Ecol Lett 5:361–366
- Harris P, Wyanski D, White B, Mikell P, Eyo P (2007) Age, growth, and reproduction of greater amberjack off the Southeastern US Atlantic Coast. Trans Am Fish Soc 136:1534–1545
- Harvey E, Cappo M (2001) Direct sensing of the size frequency and abundance of target and non-target fauna in Australian fisheries. 4–7 September 2000, Rottneest Island, Western Australia. Fisheries Research and Development Corporation
- Harvey E, Shortis M (1996) A system for stereo-video measurement of sub-tidal organisms. Mar Technol Soc J 29:10–22
- Harvey E, Shortis M, Stadler M, Cappo M (2002) A comparison of the accuracy and precision of measurements from single and stereo-video systems. Mar Technol Soc J 36:38–49
- Harvey ES, Cappo M, Butler JJ, Hall N, Kendrick GA (2007) Bait attraction affects the performance of remote underwater video stations in assessment of demersal fish community structure. Mar Ecol Prog Ser 350:245–254
- Jennings S (2000) Patterns and prediction of population recovery in marine reserves. Rev Fish Biol Fish 10:209–231
- Kelley C, Ikehara W (2006) The impacts of bottomfishing on Raita and West St. Rogatien banks in the Northwestern Hawaiian Islands. Atoll Res Bull 543:305–318
- Kelley C, Moffitt R, Smith JR (2006) Mega- to micro-scale classification and description of bottomfish essential fish habitat on four banks in the Northwestern Hawaiian Islands. Atoll Res Bull 543:319–332
- Kikkawa BS, Everson AR (1984) Gonadal maturation, fecundity, and spawning of the greater amberjack, *Seriola dumerili* (Risso), in Hawaiian waters with references to ciguatera incidences. In: Grigg RW, Tanoue KY (eds) Proc 2nd Symp Res Invest NWHI, Vol 2. University of Hawaii Sea Grant, Honolulu, HI, p161–178
- Longhurst A (2002) Murphy's law revisited: longevity as a factor in recruitment to fish populations. Fish Res 56:125–131
- Lundquist CJ, Granek EF (2005) Strategies for successful marine conservation: integrating socioeconomic, political, and scientific factors. Conserv Biol 19:1771–1778
- Merritt D, Donovan MK, Kelley C, Waterhouse L, Parke M, Wong K, Drazen JC (2011) BotCam: a baited camera system developed for non-extractive monitoring of bottomfish species. Fish Bull 109:56–67
- Micheli F, Halpern BS, Botsford LW, Warner RR (2004) Trajectories and correlates of community change in no-take marine reserves. Ecol Appl 14:1709–1723
- Moffitt R, Kobayashi D, Dinardo G (2006) Status of the Hawaiian bottomfish stocks, 2004 Admin Rep H-06-01, Pacific Islands Fish Sci Cent, Natl Mar Fish Serv, NOAA, Honolulu, HI
- Molloy PP, Goodwin NB, Côté IM, Reynolds JD, Gage MJG (2007) Sperm competition and sex change: a comparative analysis across fishes. Evolution 61:640–652
- Palumbi SR (2001) The ecology of marine protected areas. In: Bertness MD, Gaines SD, Hay ME (eds) Marine community ecology. Sinauer Associates, Sunderland, MA, p 509–530
- Palumbi SR (2004) Marine reserves and ocean neighborhoods: the spatial scale of marine populations and their management. Annu Rev Environ Resour 29:31–68
- Parke M (2007) Linking Hawaii fisherman reported commercial bottomfish catch data to potential bottomfish habitat and proposed restricted fishing areas using GIS and spatial analysis. NOAA Tech Mem NMFS-PIFSC-11, US Dep Comm, Honolulu, HI
- Polovina JJ, Moffitt RB, Ralston S, Shiota PM, Williams H (1985) Fisheries resource assessment of the Mariana Archipelago. Mar Fish Rev 47:19–25
- Priede IG, Merrett NR (1996) Estimation of abundance of abyssal demersal fishes: a comparison of data from trawls and baited cameras. J Fish Biol 49:207–216
- Priede IG, Bagley PM, Smith A, Creasey S, Merrett NR (1994) Scavenging deep demersal fishes of the Porcupine Seabight, north-east Atlantic: observations by baited camera, trap and trawl. J Mar Biol Assoc UK 74:481–498
- Ralston S, Polovina JJ (1982) A multispecies analysis of the commercial deep-sea handline fishery in Hawaii. Fish Bull 80:435–448
- Ralston S, Gooding RM, Ludwig GM (1986) An ecological survey and comparison of bottom fish resource assessments (submersible versus handline fishing) at Johnston Atoll. Fish Bull 84:141–155
- Roberts CM (1995) Rapid buildup of fish biomass in a Caribbean marine reserve. Conserv Biol 9:815–826
- Rodwell LD, Barbier EB, Roberts CM, McClanahan TR (2003) The importance of habitat quality for marine reserve fishery linkages. Can J Fish Aquat Sci 60:171–181
- Rosenberg A, Bigford TE, Leathery S, Hill RL, Bickers K (2000) Ecosystem approaches to fishery management through essential fish habitat. Bull Mar Sci 66:535–542
- Russ GR, Alcala AC (1996) Marine reserves: rates and patterns of recovery and decline of large predatory fish. Ecol Appl 6:947–961
- Russ GR, Alcala AC (2004) Marine reserves: long-term protection is required for full recovery of predatory fish populations. Oecologia 138:622–627

- Russ GR, Stockwell B, Alcala AC (2005) Inferring versus measuring rates of recovery in no-take marine reserves. *Mar Ecol Prog Ser* 292:1–12
- State of Hawai'i (2006) Hawai'i's bottomfish fishery. Land Board Briefing Paper. December 8, 2006. [http://hawaii.gov/dlnr/dar/pubs/BLNR\\_Bottomfish.pdf](http://hawaii.gov/dlnr/dar/pubs/BLNR_Bottomfish.pdf)
- Stewart J (2011) Evidence of age-class truncation in some exploited marine fish populations in New South Wales, Australia. *Fish Res* 108:209–213
- Thresher RE, Gunn JS (1986) Comparative analysis of visual census techniques for highly mobile, reef associated piscivores (Carangidae). *Environ Biol Fishes* 17:93–116
- Trenkel VM, Lorange P, Mahevas S (2004) Do visual transects provide true population density estimates for deep-water fish? *ICES J Mar Sci* 61:1050–1056
- Uchida RN, Uchiyama JH (eds) (1986) Fishery atlas of the Northwestern Hawaiian Islands. NOAA Tech Rep NMFS 38
- Watson DL, Harvey ES, Anderson MJ, Kendrick GA (2005) A comparison of temperate reef fish assemblages recorded by three underwater stereo-video techniques. *Mar Biol* 148:415–425
- Watson DL, Harvey ES, Fitzpatrick BM, Langlois TJ, She-drawi G (2010) Assessing reef fish assemblage structure: How do different stereo-video techniques compare? *Mar Biol* 157:1237–1250
- Wilcoxon F (1945) Individual comparisons by ranking methods. *Biom Bull* 1:80–83
- Williams H, Lowe M (1997) Growth rates of four Hawaiian deep slope fishes: a comparison of methods for estimating age and growth from otolith micro-increment widths. *Can J Fish Aquat Sci* 54:126–136
- Williams ID, Walsh WJ, Schroeder RE, Friedlander AM, Richards BL, Stamoulis KA (2008) Assessing the importance of fishing impacts on Hawaiian coral reef fish assemblages along regional-scale human population gradients. *Environ Conserv* 35:261–272
- Willis TJ, Babcock RC (2000) A baited underwater video system for the determination of relative density of carnivorous reef fish. *Mar Freshw Res* 51:755–763
- Willis TJ, Millar RB, Babcock RC (2000) Detection of spatial variability in relative density of fishes: comparison of visual census, angling, and baited underwater video. *Mar Ecol Prog Ser* 198:249–260
- Willis TJ, Millar RB, Babcock RC (2003) Protection of exploited fish in temperate regions: high density and biomass of snapper *Pagrus auratus* (Sparidae) in northern New Zealand marine reserves. *J Appl Ecol* 40: 214–227
- WPRFMC (1998) Preliminary draft of EFH amendment for bottomfish. Western Pacific Regional Fishery Management Council, Honolulu, HI

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